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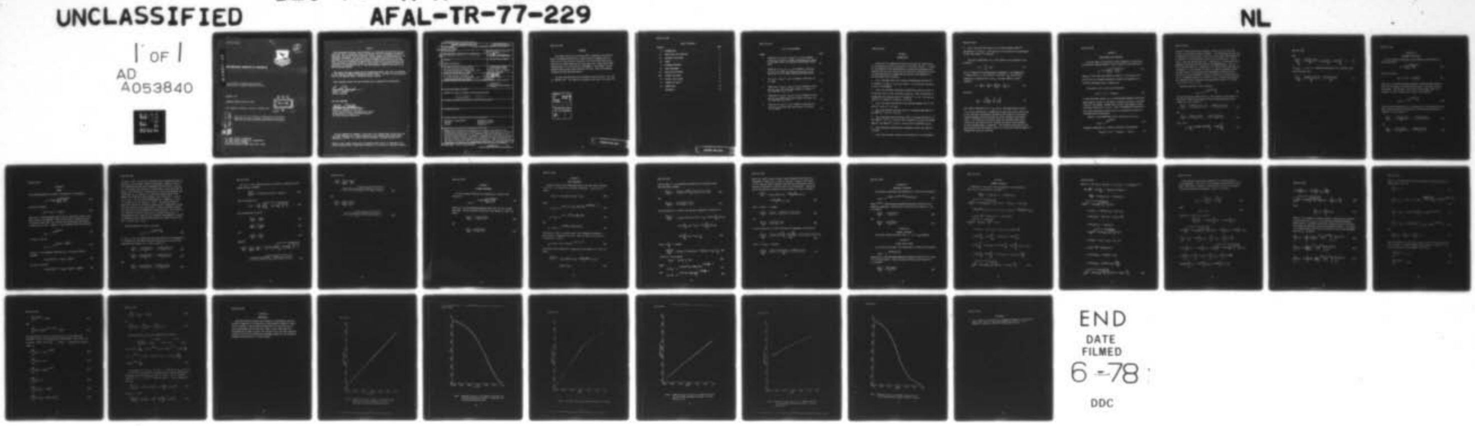

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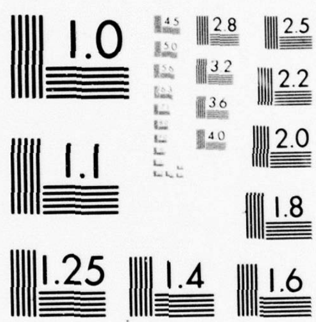

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METEOROLOGICAL SENSITIVITY OF LOWTRAN 3B

Electro-Optics & Reconnaissance Branch
Reconnaissance & Weapons Delivery Division

December 1977

TECHNICAL REPORT AFAL-TR-77-229

Final Report for Period 1 July to 1 October 1977

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AIR FORCE AVIONICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

This technical report has been reviewed and is approved for publication.

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FOR THE COMMANDER

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Mathematical expressions are developed which premit calculations of the meteorological sensitivity of Lowtran 3B, a computer code which can be used to calculate the transmittance of the atmosphere from the ultraviolet to the middle infrared portion of the spectrum. Mathematical relationships are developed which relate the water vapor line, uniformly mixed gases and ozone transmissions directly to the meteorological observables. These relationships are then used in conjunction with the existing expressions for the other atmospheric constituents to determine the meteorological sensitivity of this model.

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FOREWORD

This report describes an in-house effort conducted by the Electro-Optics and Reconnaissance Branch, Reconnaissance and Weapon Delivery Division, Air Force Avionics Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, under Project 2004, "Reconnaissance for Strike and Force Management," Task 200405, "Strike Reconnaissance Systems Characterization Facility," Work Unit 20040533, "Targeting Systems Characterization."

The work reported herein was performed during the period 1 July 1977 to 1 October 1977. The report was released by the author in October 1977.

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SECTION I
INTRODUCTION

Lowtran 3B is a computer code used to calculate the transmittance of the atmosphere from the untraviolet to the middle infrared. It begins its calculations of the transmittance at a particular wavelength over a specified path by first calculating the individual transmittance of each of eight contributors as though each were acting alone (Reference 1). The contributors are as follows:

1. $T_1(\nu)$, the water vapor line structure transmittance from 350 cm^{-1} to 14500 cm^{-1} (0.689 μm - 28.57 μm), where ν is the frequency expressed in units of wavenumbers.

2. $T_2(\nu)$, the uniformly mixed gases transmittance, which are taken to be CO_2, N_2O, CH_4, CO, and, of course, N_2 and O_2. Their contribution is included for the intervals 500 cm^{-1} to 8060 cm^{-1} (1.2 μm - 20.0 μm) and 12970 cm^{-1} to 13190 cm^{-1} (0.758 μm - 0.771 μm).

3. $T_3(\nu)$, the ozone contribution to the infrared between 575 cm^{-1} and 3270 cm^{-1} (3.06 μm - 17.39 μm).

4. $T_4(\nu)$, the nitrogen continuum, which is included between 2080 cm^{-1} and 3000 cm^{-1} (3.33 μm - 4.81 μm).

5. $T_5(\nu)$, the water vapor continuum, which is included between 670 cm^{-1} and 1350 cm^{-1} (7.41 μm - 14.93 μm) and is denoted by $T_5(\nu_{10})$, and between 2350 cm^{-1} and 3000 cm^{-1} (3.33 μm - 4.26 μm) and is denoted by $T_5(\nu_4)$.

6. $T_6(\nu)$, molecular scattering for wavelengths shorter than 3000 cm^{-1} (3.33 μm).

7. $T_7(\nu)$, due to aerosol scattering and absorption at all wavelengths.

8. $T_8(\nu)$, the ozone contribution to the visible between 13000 cm^{-1} and 23400 cm^{-1} (0.427 μm - 0.769 μm) and in the ultraviolet for wavelengths shorter than 27500 cm^{-1} (0.363 μm).

The total transmittance $T(\nu)$ is the product of the individual transmittances,

$$T(\nu) = \prod_{i=1}^{8} T_i(\nu) \qquad (1)$$

and is a function of the meteorological parameters t, the temperature in degrees Kelvin, P, the pressure in millibars, t_{dp}, the dew point temperature in degrees Kelvin, and ρ_o, the ozone density in gm/m^3. Therefore,

$$dT = \frac{\partial T}{\partial t} dt + \frac{\partial T}{\partial P} dP + \frac{\partial T}{\partial t_{dp}} dt_{dp} + \frac{\partial T}{\partial \rho_o} d\rho_o \qquad (2)$$

and since

$$\frac{\partial T}{\partial t} = \sum_{i=1}^{8} \left(\frac{\partial T_i}{\partial t} \prod_{j=1}^{8} T_{j \neq i} \right) \qquad (3)$$

with similar expressions for P, t_{dp}, and ρ_o, the meteorological sensitivity of the transmittance is determined by taking the partial derivatives of the individual transmittance expressions with respect to the meteorological parameters and substituting the results obtained into Equations 2 and 3. For simplicity, horizontal paths are considered where conditions do not vary along the path, although the results can be extended to slant variable paths, if necessary. The following considerations have been extracted from the computer code itself rather than from any supportive documentation which was available.

SECTION II

WATER VAPOR LINE STRUCTURE

For water vapor line structure, Lowtran 3B begins by calculating the equivalent absorber amount in units of gm/m^2 for the entire path,

$$\omega_1 = 0.1\rho_\omega R\left(\frac{P}{P_o}\right)^{0.9}\left(\frac{t_o}{t}\right)^{0.45} \tag{4}$$

where ρ_ω is the water vapor density in gm/m^3, R is the range in km, and P_o and t_o are standard atmospheric pressure and temperature in millibars and degrees Kelvin, respectively.

The quantity $p_1(\nu)$, given by the expression

$$p_1(\nu) = c_1\ (\nu) + \log_{10}(\omega_1) \tag{5}$$

is then calculated, where $c_1(\nu)$ is the wavelength dependent coefficient whose numerical values for the bands of interest are given in the data listing of the program. Another data listing in the program is then used which relates $p_1(\nu)$ to $T_1(\nu)$. Thus, no mathematical relationship exists which expresses the water vapor line transmission directly to the meteorological observables.

However, it was determined that an expression of the form

$$T_1(\nu) = e^{-a_1 10^{b_1 p_1(\nu)}} \tag{6}$$

adequately determines $T_1(\nu)$ from $p_1(\nu)$ directly, and therefore

$$\log_{10}(-\ln T_1(\nu)) = \log_{10}(a_1) + b_1 p_1(\nu) \tag{7}$$

A plot of the left-hand side of Equation 7 versus $p_1(\nu)$ for the data listed in the program is shown in Figure 1. The listed data was then used to determine the coefficients a_1 and b_1 by a first order least squares fit of Equation 7, using the values of $(p_1(\nu), T_1(\nu))$ from $T_1(\nu) = 0.90$ to $T_1(\nu) = 0.02$, but omitting the $T_1(\nu) = 0.88$ and $T_1(\nu) = 0.86$ points which appeared inconsistent with the trend of the remaining data. The fit values obtained where $a_1 = 0.07054$ and $b_1 = 0.5523$, and the resulting form of Equation 7 is also plotted in Figure 1 to show the agreement between the data listed in the program and the mathematical expression used. The results are also compared in Figure 2, where $T_1(\nu)$ is plotted versus $p_1(\nu)$. A standard deviation of 0.0037 for $T_1(\nu)$, derived from Equation 6 and compared to the listed data, was obtained for values of $T_1(\nu)$ from $T_1(\nu) = 0.96$ to $T_1(\nu) = 0.02$.

Combining Equations 5 and 6, we obtain

$$T_1(\nu) = e^{-a_1 10^{b_1 c_1(\nu)} \omega_1^{b_1}}, \tag{8}$$

and substituting the expression for ω_1 from Equation 4 into Equation 8, and taking the partial derivatives of the resulting expression with respect to t and P results in

$$\frac{\partial T_1(\nu)}{\partial t} = -\frac{0.45 b_1 T_1(\nu)\ \ell n\ T_1(\nu)}{t} = -\frac{0.248 T_1(\nu)\ \ell n\ T_1(\nu)}{t} \tag{9}$$

and

$$\frac{\partial T_1(\nu)}{\partial P} = \frac{0.9 b_1 T_1(\nu) \ell n T_1(\nu)}{P} = \frac{0.497\ T_1(\nu) \ell n T_1(\nu)}{P} \tag{10}$$

Also, since

$$\rho_\omega = \frac{t_o}{t_{dp}} e^{\left(18.9766 - 14.9595 \frac{t_o}{t_{dp}} - 2.4388 \frac{t_o^2}{t_{dp}^2}\right)} \tag{11}$$

then

$$\frac{\partial T_1(\nu)}{\partial t_{dp}} = \frac{b_1 T_1(\nu) \ell n \; T_1(\nu)}{t_{dp}} \{14.9595 \frac{t_o}{t_{dp}} + 4.8776 \frac{t_o^2}{t_{dp}^2} - 1\} \quad (12)$$

If $t_o/t_{dp} \simeq 1$, which is a reasonable approximation for horizontal paths near the ground, then

$$\frac{\partial T_1(\nu)}{\partial t_{dp}} = \frac{18.84 b_1 T_1(\nu) \ell n T_1(\nu)}{t_{dp}} = \frac{10.4 T_1(\nu) \ell n T_1(\nu)}{t_{dp}} \quad (13)$$

SECTION III

UNIFORMLY MIXED GASES

For the uniformly mixed gases, Lowtran begins by calculating the similar expression

$$\omega_2 = R\left(\frac{P}{P_o}\right)^{7/4}\left(\frac{t_o}{t}\right)^{11/8} \tag{14}$$

and then calculates

$$p_2(\nu) = c_2(\nu) + \log_{10}\left(\omega_2\right) , \tag{15}$$

where $c_2(\nu)$ is another wavelength-dependent coefficient whose numerical values for the bands of interest are also given in the data listing of the program. The same data listing table used for water vapor line structure is used to relate $p_2(\nu)$ to $T_2(\nu)$, and therefore

$$T_2(\nu) = e^{-a_1 10^{b_1 c_2(\nu)} \omega_2^{b_1}} \tag{16}$$

Substituting the expression for ω_2 from Equation 14 into Equation 16, and again taking the partial derivatives of the resulting expression with respect to t and P results in

$$\frac{\partial T_2(\nu)}{\partial t} = -\frac{11 b_1 T_2(\nu) \ln T_2(\nu)}{8t} = -\frac{0.759 T_2(\nu) \ln T_2(\nu)}{t} \tag{17}$$

and

$$\frac{\partial T_2(\nu)}{\partial P} = \frac{7 b_1 T_2(\nu) \ln T_2(\nu)}{4P} = \frac{0.966 T_2(\nu) \ln T_2(\nu)}{P} \tag{18}$$

SECTION IV
OZONE

The infrared absorption for ozone is evaluated by first computing

$$\omega_3 = 46.667\rho_o R\left(\frac{P}{P_o}\right)^{2/5}\left(\frac{t_o}{t}\right)^{1/5} \tag{19}$$

and then calculating

$$p_3(\nu) = c_3(\nu) + \log_{10}(\omega_3) \tag{20}$$

where $c_3(\nu)$ is the wavelength coefficient for ozone and is given in the data listing of the program. A data listing table, different from the one used for water vapor line structure and the uniformly mixed gases, relates $p_3(\nu)$ to $T_3(\nu)$. However, it was determined that the expressions

$$T_3(\nu) = e^{-a_2 10^{b_2 p_3(\nu)}} \tag{21}$$

for $T_3(\nu) \geq 0.36$ and

$$T_3(\nu) = e^{-a_3 10^{b_3 p_3(\nu) + d_3 p_3^2(\nu)}} \tag{22}$$

for $T_3(\nu) < 0.36$ adequately determines $T_3(\nu)$ from $p_3(\nu)$ directly. Therefore

$$\log_{10}(-\ell n T_3(\nu)) = \log_{10} a_2 + b_2 p_3(\nu) \tag{23}$$

for $T_3(\nu) \geq 0.36$ and

$$\log_{10}(-\ell n T_3(\nu)) = \log_{10} a_3 + b_3 p_3(\nu) + d_3 p_3^2(\nu) \tag{24}$$

for $T_3(\nu) < 0.36$. A plot of the left-hand side of Equations 23 and 24 versus $p_3(\nu)$ for the data listed in the program is shown in Figure 3. The listed data was then used to determine the coefficients a_2 and b_2 by a first order least squares fit of Equation 23, using the values of $(p_3(\nu), T_3(\nu))$ from $T_3(\nu) = 0.90$ to $T_3(\nu) = 0.36$, and to determine the coefficients a_3, b_3, and d_3 by a second order least squares fit of Equation 24, using the values of $(p_3(\nu), T_3(\nu))$ from $T_3(\nu) = 0.34$ to $T_3(\nu) = 0.02$. The fit values obtained were $a_2 = 0.0589$, $b_2 = 0.729$, $a_3 = 0.0909$, $b_3 = 0.752$, and $d_3 = -0.0774$. The resulting forms of Equations 23 and 24 are plotted in Figures 4 and 5 respectively, along with the pertinent listed program data, to show the agreement between the listed data and the mathematical expressions used. The results are also compared in Figure 6, where $T_3(\nu)$ is plotted versus $p_3(\nu)$. A standard deviation of .0025 for $T_3(\nu)$ obtained from Equations 21 and 22 and compared to the listed data was obtained for values of $T_3(\nu)$ from $T_3(\nu) = 0.96$ to $T_3(\nu) = 0.02$.

Combining Equations 20 and 21, we obtain

$$T_3(\nu) = e^{-a_2 10^{b_2 c_3(\nu)} \omega_3^{b_2}} \tag{25}$$

for $T_3(\nu) \geq 0.36$, and substituting the expression for ω_3 from Equation 19 into Equation 25, and taking the partial derivatives of the resulting expression with respect to t, P, and ρ_o results in

$$\frac{\partial T_3(\nu)}{\partial t} = -\frac{b_2 T_3(\nu) \ln T_3(\nu)}{5t} = -\frac{0.146 T_3(\nu) \ln T_3(\nu)}{t} \tag{26}$$

$$\frac{\partial T_3(\nu)}{\partial P} = \frac{2b_2 T_3(\nu) \ln T_3(\nu)}{5P} = \frac{0.292 T_3(\nu) \ln T_3(\nu)}{P} \tag{27}$$

and

$$\frac{\partial T_3(\nu)}{\partial \rho_o} = \frac{b_2 T_3(\nu) \ln T_3(\nu)}{\rho_o} = \frac{0.729 T_3(\nu) \ln T_3(\nu)}{\rho_o} \tag{28}$$

For $T_3(\nu) < 0.36$, taking the partial derivative of Equation 22 with respect to $p_3(\nu)$ we obtain

$$\frac{\partial T_3(\nu)}{\partial p_3(\nu)} = (\ln 10) T_3(\nu) \ln T_3(\nu) \{b_3 + 2d_3 p_3(\nu)\} \tag{29}$$

Since from Equation 24

$$p_3(\nu) = -\frac{b_3}{2d_3} - \sqrt{\frac{b_3^2}{4d_3^2} + \frac{1}{d_3}\log_{10}\left(-\frac{\ln T_3(\nu)}{a_3}\right)} \tag{30}$$

and from Equations 19 and 20

$$\frac{\partial p_3(\nu)}{\partial t} = -\frac{\log_{10}e}{5t} \tag{31}$$

$$\frac{\partial p_3(\nu)}{\partial P} = \frac{2\log_{10}e}{5P} \tag{32}$$

and

$$\frac{\partial p_3(\nu)}{\partial \rho_o} = \frac{\log_{10}e}{\rho_o} \tag{33}$$

Therefore

$$\frac{\partial T_3(\nu)}{\partial t} = \frac{\partial T_3(\nu)}{\partial p_3(\nu)} \frac{\partial p_3(\nu)}{\partial t} = -\frac{T_3(\nu)\ln T_3(\nu)\sqrt{b_3^2 + 4d_3\log_{10}\left(-\frac{\ln T_3(\nu)}{a_3}\right)}}{5t}$$

$$= -\frac{0.20 T_3(\nu)\ln T_3(\nu)\sqrt{0.565 - 0.3095\log_{10}(-11\ln T_3(\nu))}}{t} \tag{34}$$

$$\frac{\partial T_3(\nu)}{\partial P} = \frac{\partial T_3(\nu)}{\partial p_3(\nu)} \; \frac{\partial p_3(\nu)}{\partial P}$$

$$= \frac{0.40T_3(\nu)\ln T_3(\nu)\sqrt{0.565-0.3095\log_{10}(-11\ln T_3(\nu))}}{P} \qquad (35)$$

and

$$\frac{\partial T_3(\nu)}{\partial \rho_o} = \frac{\partial T_3(\nu)}{\partial p_3(\nu)} \; \frac{\partial p_3(\nu)}{\partial \rho_o}$$

$$= \frac{T_3(\nu)\ln T_3(\nu)\sqrt{0.565-0.3095\log_{10}(-11\ln T_3(\nu))}}{\rho_o} \qquad (36)$$

SECTION V

NITROGEN CONTINUUM

For the nitrogen continuum, the transmission is given by the expression

$$T_4(\nu) = e^{-0.8c_4(\nu)R\left(\frac{P}{P_o}\right)^2\left(\frac{t_o}{t}\right)^{3/2}} \tag{37}$$

where $c_4(\nu)$ is the wavelength-dependent coefficient for the nitrogen continuum. Taking the partial derivatives with respect to t and P we obtain

$$\frac{\partial T_4(\nu)}{\partial t} = -\frac{1.5T_4(\nu)\ln T_4(\nu)}{t} \tag{38}$$

and

$$\frac{\partial T_4(\nu)}{\partial P} = \frac{2T_4(\nu)\ln T_4(\nu)}{P} \tag{39}$$

SECTION VI

WATER CONTINUUM

Lowtran 3B treats the transmittance due to the water vapor continuum in the 3.5 - 4.2 μm and 8-14 μm regions differently. In the 8-14 μm region

$$T_5(\nu_{10}) = T_5'(\nu_{10})T_5''(\nu_{10})T_5'''(\nu_{10}) \tag{40}$$

where

$$T_5'(\nu_{10}) = e^{-4.56 \times 10^{-7} c_5(\nu,296)\rho_\omega{}^2 Rte^{6.08(296/t - 1)}} \tag{41}$$

$$T_5''(\nu_{10}) = e^{9.12 \times 10^{-10} c_5(\nu,296)\rho_\omega{}^2 Rt} \tag{42}$$

and

$$T_5'''(\nu_{10}) = e^{-0.0002c_5(\nu,296)\rho_\omega R\, P/P_o} \tag{43}$$

The term $c_5(\nu, 296)$ is the water vapor (self-broadened) attenuation coefficient at a temperature of 296°K, which for the 8-14 μm region of the spectrum is given as

$$c_5(\nu, 296) = 4.18 + 5578.0e^{-7.87 \times 10^{-3}\nu} \tag{44}$$

Taking the partial derivative of Equation 40 with respect to t and P, we obtain

$$\frac{\partial T_5(\nu_{10})}{\partial t} = T_5(\nu_{10})\{\frac{1}{t}\ell n T_5'(\nu_{10}) - \frac{6.08 \times 296}{t^2}\ell n T_5'(\nu_{10}) + \frac{1}{t}\ell n T_5''(\nu_{10})\} \tag{45}$$

which if $296/t \simeq 1$, a reasonable approximation for horizontal paths near the ground, becomes

$$\frac{\partial T_5(\nu_{10})}{\partial t} = \frac{T_5(\nu_{10})\{-5.08 \ln T_5'(\nu_{10}) + \ln T_5''(\nu_{10})\}}{t} \tag{46}$$

and

$$\frac{\partial T_5(\nu_{10})}{\partial P} = \frac{T_5(\nu_{10}) \ln T_5'''(\nu_{10})}{P} \tag{47}$$

By using Equation 11 to obtain the dew point dependence of Equation 40,

$$\frac{\partial T_5(\nu_{10})}{\partial t_{dp}} = T_5(\nu_{10})\{-2 \ln T_5(\nu_{10}) + \ln T_5'''(\nu_{10}) + 29{,}919 \frac{t_o}{t_{dp}} \ln T_5(\nu_{10})$$

$$- 14.96 \frac{t_o}{t_{dp}} \ln T_5'''(\nu_{10}) + 9.76 \frac{t_o^2}{t_{dp}^2} \ln T_5(\nu_{10})$$

$$- 4.88 \frac{t_o^2}{t_{dp}^2} \ln T_5'''(\nu_{10})\} \frac{1}{t_{dp}} \tag{48}$$

which, if $\frac{t_o}{t_{dp}} \simeq 1$, becomes

$$\frac{\partial T_5(\nu_{10})}{\partial t_{dp}} = T_5(\nu_{10})\{ 37.57 \ln T_5(\nu_{10}) - 18.84 \ln T_5'''(\nu_{10})\} \frac{1}{t_{dp}} \tag{49}$$

In the 3.5 - 4.2 μm region

$$T_5(\nu_4) = T_5'(\nu_4)\, T_5''(\nu_4) \tag{50}$$

where

$$T_5'(\nu_4) = e^{-4.012\times10^{-7} c_5(\nu,296)\rho_\omega^2 t \, Re^{4.56(\frac{296}{t} -1)}} \tag{51}$$

and

$$T_5''(\nu_4) = e^{-0.012\, c_5(\nu,296)\rho_\omega \frac{RP}{P_o} e^{4.56(\frac{296}{t} -1)}} \tag{52}$$

where $c_5(\nu, 296)$ is again the water vapor attenuation coefficient at a temperature of 296°K, but is given in the data listing of the program for this spectral region instead of the empirical relationship given by Equation 44 and which is used for the 8-14 μm calculations. Taking the partial derivatives of Equation 49 with respect to t and P, we obtain:

$$\frac{\partial T_5(\nu_4)}{\partial t} = T_5(\nu_4)\{ \frac{1}{t}\ell n T_5'(\nu_4) - \frac{4.56 \times 296}{t^2}\ell n T_5'(\nu_4) - \frac{4.56 \times 296}{t^2}\ell n\, T_5''(\nu_4)\} \tag{53}$$

which, if 296/t ≃ 1, becomes

$$\frac{\partial T_5(\nu_4)}{\partial t} = \frac{T_5(\nu_4)\{ - 3.56\ell n T_5(\nu_4) - \ell n T_5''(\nu_4)\}}{t} \tag{54}$$

and

$$\frac{\partial T_5(\nu_4)}{\partial P} = \frac{T_5(\nu_4)\ell n T_5''(\nu_4)}{P} \tag{55}$$

By using Equation 11 to obtain the dew point dependence of Equation 50,

$$\frac{\partial T_5(\nu_4)}{\partial t_{dp}} = \frac{T_5(\nu_4)\{ 14.96 \frac{t_o}{t_{dp}} + 4.88 \frac{t_o{}^2}{t_{dp}{}^2} - 1\}\{ 2\ell n T_5'(\nu_4) + \ell n T_5''(\nu_4)}{t_{dp}} \tag{56}$$

which, if $t_o/t_{dp} \simeq 1$, becomes

$$\frac{\partial T_5(\nu_4)}{\partial t_{dp}} = \frac{T_5(\nu_4)\ \{37.67\ell n T_5(\nu_4) - 18.84\ell n T_5''(\nu_4)\}}{t_{dp}} \tag{57}$$

SECTION VII

MOLECULAR SCATTERING

For molecular scattering, the transmission is given by the expression

$$T_6(\nu) = e^{-9.807 \times 10^{-20} \nu^{4.0117} R(P/P_o)(t_o/t)} \tag{58}$$

where $\nu^{4.0117}$ is the wavelength-dependent attenuation coefficient for molecular scattering. Taking partial derivatives with respect to t and P, we obtain

$$\frac{\partial T_6(\nu)}{\partial t} = -\frac{T_6(\nu)\ell n T_6(\nu)}{t} \tag{59}$$

and

$$\frac{\partial T_6(\nu)}{\partial P} = \frac{T_6(\nu)\ell n T_6(\nu)}{P} \tag{60}$$

SECTION VIII

AEROSOL SCATTERING

The aerosol scattering term is not t, P, ρ_o, or t_{dp} dependent.

SECTION IX

VISIBLE AND UV OZONE

For visible and UV ozone, the transmission is given by the expression

$$T_8(\nu) = e^{-46.667 c_8(\nu)\rho_o R}$$

where $c_8(\nu)$ is the wavelength-dependent attenuation coefficient for ozone in the visible and UV. Taking the partial derivative with respect to ρ_o, we obtain

$$\frac{\partial T_8(\nu)}{d\rho_o} = \frac{T_8(\nu)\ell n T_8(\nu)}{\rho_o} \tag{61}$$

SECTION X

SUMMARY OF RESULTS

Combining all the results by using Equation 3 and substituting these results into Equation 2, we obtain

$$
\begin{aligned}
\frac{dT(\nu)}{T(\nu)} = &\{-0.45b_1 \ln T_1(\nu) - 1.375b_1 \ln T_2(\nu) - \\
&0.20\sqrt{b_i^{\,2} + 4d_i \log_{10}\left(-\frac{\ln T_3(\nu)}{a_i}\right)}\, \ln T_3(\nu) - 1.5 \ln T_4(\nu) + \ln T_5'(\nu_{10}) \\
&- \frac{6.08 \times 296}{t} \ln T_5'(\nu_{10}) + \ln T_5''(\nu_{10}) + \ln T_5'(\nu_4) - \frac{4.56 \times 296}{t} \ln T_5(\nu_4) \\
&- \ln T_6(\nu)\} \frac{dt}{t} + \{0.9b_1 \ln T_1(\nu) + 1.75\, b_1 \ln T_2(\nu) + \\
&0.40\sqrt{b_i^{\,2} + 4d_i \log_{10} - \frac{\ln T_3(\nu)}{a_i}}\, \ln T_3(\nu) \\
&+ 2.0 \ln T_4(\nu) + \ln T_5'''(\nu_{10}) + \ln T_5''(\nu_4) + \ln T_6(\nu)\} \frac{dP}{P} \\
&+\{(14.96 \frac{t_o}{t_{dp}} + 4.88 \frac{t_o^{\,2}}{t_{dp}^{\,2}} - 1) b_1 \ln T_1(\nu) + (29.92 \frac{t_o}{t_{dp}} \\
&+ 9.76 \frac{t_o^{\,2}}{t_{dp}^{\,2}} - 2) \ln T_5(\nu_{10}) + (1 - 14.96 \frac{t_o}{t_{dp}} - 4.88 \frac{t_o^{\,2}}{t_{dp}^{\,2}}) \ln T_5'''(\nu_{10}) \\
&+ (14.96 \frac{t_o}{t_{dp}} + 4.88 \frac{t_o^{2}}{t_{dp}^{\,2}} - 1)\ (2 \ln T_5'(\nu_4) + \ln T_5''(\nu_4))\} \frac{dt_{dp}}{t_{dp}} + \\
&\{\sqrt{b_1^{\,2} + 4d_i \log_{10}\left(-\frac{\ln T_3(\nu)}{a_i}\right)}\, \ln T_3(\nu) + \ln T_8(\nu)\} \frac{d\rho_o}{\rho_o} \qquad (62)
\end{aligned}
$$

where i = 2 for $T_3(\nu) \geq 0.36$ and i = 3 for $T_3(\nu) < 0.36$ and $d_2 = 0$.

When $\frac{296}{t} \simeq 1$ and $\frac{t_o}{t_{dp}} \simeq 1$, Equation 62 reduces to

$$\frac{dT(\nu)}{T(\nu)} = \{-0.45b_1 \ln T_1(\nu) - 1.375b_1 \ln T_2(\nu) -$$

$$0.20\sqrt{b_i^2 + 4d_i \log_{10}\left(-\frac{\ln T_3(\nu)}{a_i}\right)}\ \ln T_3(\nu)$$

$$- 1.5\ln T_4(\nu) - 5.08\ln T_5'(\nu_{10}) + \ln T_5''(\nu_{10})$$

$$- 3.56\ln T_5(\nu_4) - \ln T_5''(\nu_4) - \ln T_6(\nu)\}\ \frac{dt}{t}$$

$$+ \{0.9b_1 \ln T_1(\nu) + 1.75b_1 \ln T_2(\nu)$$

$$+ 0.40\sqrt{b_i^2 + 4d_i \log_{10}\left(-\frac{\ln T_3(\nu)}{a_i}\right)}\ \ln T_3(\nu)$$

$$+ 2.0\ln T_4(\nu) + \ln T_5'''(\nu_{10}) + \ln T_5''(\nu_4)$$

$$+ \ln T_6(\nu)\}\ \frac{dP}{P} + \{18.84b_1 \ln T_1(\nu)$$

$$+ 37.67\ln T_5(\nu_{10}) - 18.84\ln T_5'''(\nu_{10})$$

$$+ 37.67\ln T_5(\nu_4) - 18.84\ln T'_5(\nu_4)\}\ \frac{dt_{dp}}{t_{dp}} +$$

$$\{\sqrt{b_i^2 + 4d_i \log_{10}\left(\frac{-\ln T_3(\nu)}{a_i}\right)}\ \ln T_3(\nu) + \ln T_8(\nu)\}\ \frac{d\rho_o}{\rho_o} \qquad (63)$$

These derivations have been performed for a small band about a single wavenumber. The results can be expanded to determine the effect over a wider band of interest by utilizing the results of the average transmission between two wavenumbers ν_2 and ν_1 as follows

$$T(\nu_2-\nu_1) = \frac{\sum_{j=1}^{N} T(\nu_j)\Delta\nu}{\nu_2-\nu_1} = \frac{\sum_{j=1}^{N} T(\nu_j)}{N} \tag{64}$$

where

$$N\Delta\nu = \nu_2-\nu_1 \tag{65}$$

Therefore, if each $T(\nu_j) \approx T(\nu_2-\nu_1)$

$$\frac{dT(\nu_2-\nu_1)}{T(\nu_2-\nu_1)} = \{-0.45b_1 \ell n\prod_{j=1}^{N} T_1(\nu_j) - 1.375b_1 \ell n\prod_{j=1}^{N} T_2(\nu_j) -$$

$$0.20 \sum_{j=1}^{N} \sqrt{b_i^{\,2} + 4d_i \log_{10}\left(-\frac{\ell n T_3(\nu_j)}{a_i}\right)}\, \ell n T_3(\nu_j) - 1.5\ell n\prod_{j=1}^{N} T_4(\nu_j) - 5.08\ell n\prod_{j=1}^{N} T_5{}'(\nu_{10_j})$$

$$+ \ell n\prod_{j=1}^{N} T_5{}''(\nu_{10_j}) - 3.56\ell n\prod_{j=1}^{N} T_5(\nu_{4_j}) - \ell n\prod_{j=1}^{N} T_5{}''(\nu_{4_j}) - \ell n\prod_{j=1}^{N} T_6(\nu_j)\} \frac{dt}{Nt} +$$

$$\{0.9b_1 \ell n\prod_{j=1}^{N} T_1(\nu_j) + 1.75b_1 \ell n\prod_{j=1}^{N} T_2(\nu_j) + 0.40 \sum_{j=1}^{N} \sqrt{b_i^{\,2} + 4d_i \log_{10}\left(-\frac{\ell n T_3(\nu_j)}{a_i}\right)}\, \ell n T_3(\nu_j)$$

$$+ 2.0\ell n\prod_{j=1}^{N} T_4(\nu_j) + \ell n\prod_{j=1}^{N} T_5{}'''(\nu_{10_j}) + \ell n\prod_{j=1}^{N} T_5{}'(\nu_{4_j}) + \ell n\prod_{j=1}^{N} T_6(\nu_j)\} \frac{dP}{NP} +$$

$$\{18.84b_1 \ell n\prod_{j=1}^{N} T_1(\nu_j) + 37.67\ell n\prod_{j=1}^{N} T_5(\nu_{10_j}) - 18.84\ell n\prod_{j=1}^{N} T_5{}'''(\nu_{10_j}) +$$

$$37.67\ln\prod_{j=1}^{N} T_5(\nu_{4_j}) - 18.84\ln\prod_{j=1}^{N} T_5'(\nu_{4_j})\}\frac{dt_{dp}}{Nt_{dp}} +$$

$$\{\sum_{j=1}^{N}\sqrt{b_i^{\,2} + 4d_i\log_{10}\left(-\frac{\ln T_3(\nu_j)}{a_i}\right)}\ln T_3(\nu_j) + \ln\prod_{j=i}^{N} T_8(\nu_j)\}\frac{d\rho_o}{N\rho_o} \tag{66}$$

Since

$$\ln\prod_{j=1}^{N} T_i(\nu_j) = M_i\sum_{j=1}^{N} f(c_i(\nu_j)) \tag{67}$$

where M_i is the product of various constants, meteorological parameters, and the range, and $f(c_i(\nu_j))$ is the functional wavelength-dependent coefficient for a particular contributor, Equation 66 can be simplified even further by selecting a particular wavelength interval. For example, if the meteorological sensitivity is desired for the 715-1250 wavenumber band (8.0 μm - 13.98 μm),

$$\ln\prod_{j=1}^{N} T_1(\nu_j) = -a_1\left(0.1\rho_\omega R\left(\frac{P}{P_o}\right)^{0.9}\left(\frac{t_o}{t}\right)^{0.45}\right)^{b_1}\sum_{j=1}^{N} 10^{b_1 c_1(\nu_j)} \tag{68}$$

$$\ln\prod_{j=1}^{N} T_3(\nu_j) = -a_1\left(R\left(\frac{P}{P_o}\right)^{7/4}\left(\frac{t_o}{t}\right)^{11/8}\right)^{b_1}\sum_{j=1}^{N} 10^{b_1 c_2(\nu_j)} \tag{69}$$

$$\ln\prod_{j=1}^{N} T_3(\nu_j) = -a_2\left(46.667\ \rho_o R\left(\frac{P}{P_o}\right)^{2/5}\left(\frac{t_o}{t}\right)^{1/5}\right)^{b_2}\sum_{j=1}^{N} 10^{b_2 c_3(\nu_j)} \tag{70}$$

where it is assumed that for horizontal paths near the ground $T_3(\nu_j)$ is always greater than 0.36

$$\ell n \prod_{j=1}^{N} T_4(\nu_j) = 0, \qquad (71)$$

$$\ell n \prod_{j=1}^{N} T_5'(\nu_{10_j}) = -4.56 \times 10^{-7} \rho_\omega{}^2 Rte^{6.08\left(\frac{296}{t}-1\right)} \sum_{j=1}^{N}(4.18 + 5578e^{-7.87\times10^{-3}\nu_j}) \qquad (72)$$

$$\ell n \prod_{j=1}^{N} T_5''(\nu_{10_j}) = 9.12\times10^{-10} \rho_\omega{}^2 Rt \sum_{j=1}^{N}(4.18 + 5578e^{-7.87\times10^{-3}\nu_j}) \qquad (73)$$

$$\ell n \prod_{j=1}^{N} T_5'''(\nu_{10_j}) = -0.0002 \rho_\omega R \frac{P}{P_o} \sum_{j=1}^{N} (4.18 + 5578e^{-7.87\times10^{-3}\nu_j}) \qquad (74)$$

and

$$\ell n \prod_{j=1}^{N} T_5(\nu_{4_j}) = \ell n \prod_{j=1}^{N} T_6(\nu_j) = \ell n \prod_{j=1}^{N} T_8(\nu_j) = 0 \qquad (75)$$

where the summation is over 108 ν_j values of the coefficients, given at five wavenumber increments between the wavenumbers 715-1250 cm^{-1}. The values obtained over the wavenumber interval are

$$\sum_{j=1}^{108} 10^{b_1 c_1(\nu_j)} = 171.1 \qquad (76)$$

$$\sum_{j=1}^{108} 10^{b_1 c_2(\nu_j)} = 116.6 \qquad (77)$$

$$\sum_{j=1}^{108} 10^{b_2 c_3(\nu_j)} = 964.5 \qquad (78)$$

and

$$\sum_{j=1}^{108} (4.18 + 5578e^{-7.87 \times 10^{-3}\nu_j}) = 964.3, \qquad (79)$$

using the values of $c_1(\nu_j)$, $c_2(\nu_j)$, and $c_3(\nu_j)$ at the appropriate wavenumber listed in the data section of the program. Since N=108, and by using t = 296°K, R=8 km, $\frac{t_o}{t} \simeq 1$, and $\frac{p}{p_o} \simeq 1$, Equations 68 through 75 reduce to

$$\ell n \prod_{j=1}^{108} T_1(\nu_j) = -10.7\rho_\omega^{0.5523} \qquad (80)$$

$$\ell n \prod_{j=1}^{108} T_2(\nu_j) = -25.9 \qquad (81)$$

$$\ell n \prod_{j=1}^{108} T_3(\nu_j) = -4261\rho_o^{0.729} \qquad (82)$$

$$\ell n \prod_{j=1}^{108} T_4(\nu_j) = 0 \qquad (83)$$

$$\ell n \prod_{j=1}^{108} T_5'(\nu_{10_j}) = -1.04\rho_\omega^2 \qquad (84)$$

$$\ell n \prod_{j=1}^{108} T_5''(\nu_{10_j}) = 2.08 \times 10^{-3}\rho_\omega^2 \qquad (85)$$

$$\ln \prod_{j=1}^{108} T_5'''(\nu_{10_j}) = -1.543\rho_\omega \tag{86}$$

and

$$\ln \prod_{j=1}^{108} T_5(\nu_{4_j}) = \ln\prod_{j=1}^{108} T_6(\nu_j) = \ln\prod_{j=1}^{108} T_8(\nu_j) = 0 \tag{87}$$

Substituting these results into Equation 66, we obtain:

$$\frac{dT(\nu_2-\nu_1)}{T(\nu_2-\nu_1)} = \{2.66\rho_\omega^{0.5523} + 19.7 + 621\rho_o^{0.729} + 5.28\rho_\omega^{2} -$$

$$2.08 \times 10^{-3}\rho_\omega^{2}\}\frac{dt}{108t} - \{5.32\rho_\omega^{0.5523} + 25.0 + 1242\rho_o^{0.729} + 1.543\rho_\omega\}\frac{dP}{108P}$$

$$-\{111.3\rho_\omega^{0.5523} + 39.18\rho_\omega^{2} - 0.078\rho_\omega^{2} + 58.12\rho_\omega - 29.06\rho_\omega\}\frac{dt_{dp}}{108t_{dp}}$$

$$-\{3106\rho_o^{0.729}\}\frac{d\rho_o}{108\rho_o} \tag{88}$$

From Equation 11, for $t_{dp} = 273.15°K$, $\rho_\omega = 4.84$ and for $t_{dp} = 303.15°K$, $\rho_\omega = 30.36$, which constitutes a reasonable range of dew point temperatures encountered for a horizontal path near the ground. Also a reasonable value for ρ_o is $\rho_o = 5 \times 10^{-5}$. Therefore using $\rho_\omega = 4.84$ in Equation 88, we obtain

$$\frac{dT(\nu_2-\nu_1)}{T(\nu_2-\nu_1)} = 1.39\frac{dt}{t} - 0.43\frac{dP}{P} - 12.25\frac{dt_{dp}}{t_{dp}} - 0.021\frac{d\rho_o}{\rho_o} \tag{89}$$

and for $\rho_\omega = 30.36$

$$\frac{dT(\nu_2-\nu_1)}{T(\nu_2-\nu_1)} = 45.39\frac{dt}{t} - 1.0\frac{dP}{P} - 349\frac{dt_{dp}}{t_{dp}} - 0.021\frac{d\rho_o}{\rho_o} \tag{90}$$

SECTION XI

CONCLUSIONS

Equations 89 and 90 express the tolerances in temperature, pressure, dew point temperature, and ozone density measurements allowable to obtain a given accuracy in the transmission prediction of Lowtran 3B over the 8-14 μm wavelength band for the given range of water vapor densities. The method can be used to predict the tolerances over any other wavelength range by calculating the appropriate wavenumber summations and proceeding through the calculations in a similar manner.

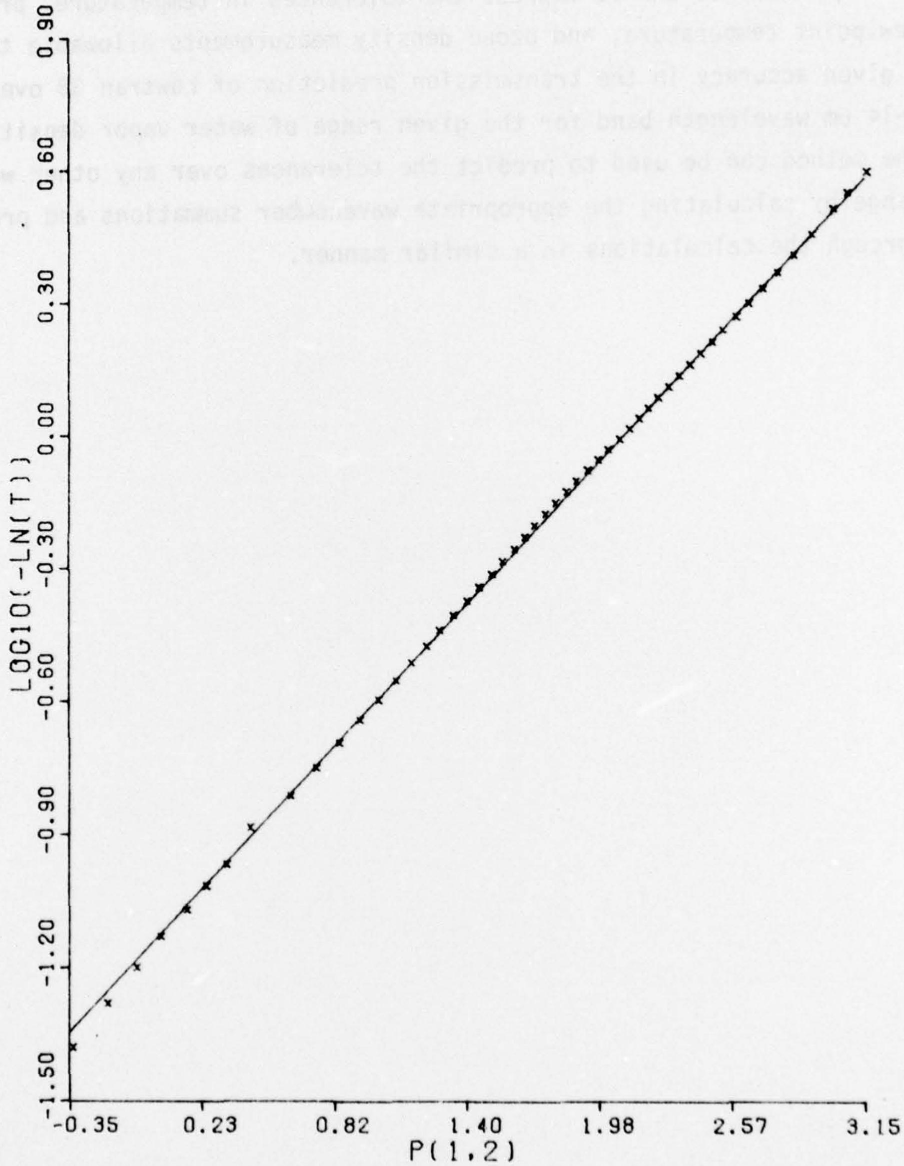

Figure 1. Comparison of $(p_{1,2}(\nu))$, $\log_{10}(-\ln T_{1,2}(\nu)))$ Computer Listed data (X) and First Order Least Squares Fit Values (-) for Water Vapor Line Structure and Uniformly Mixed Gases

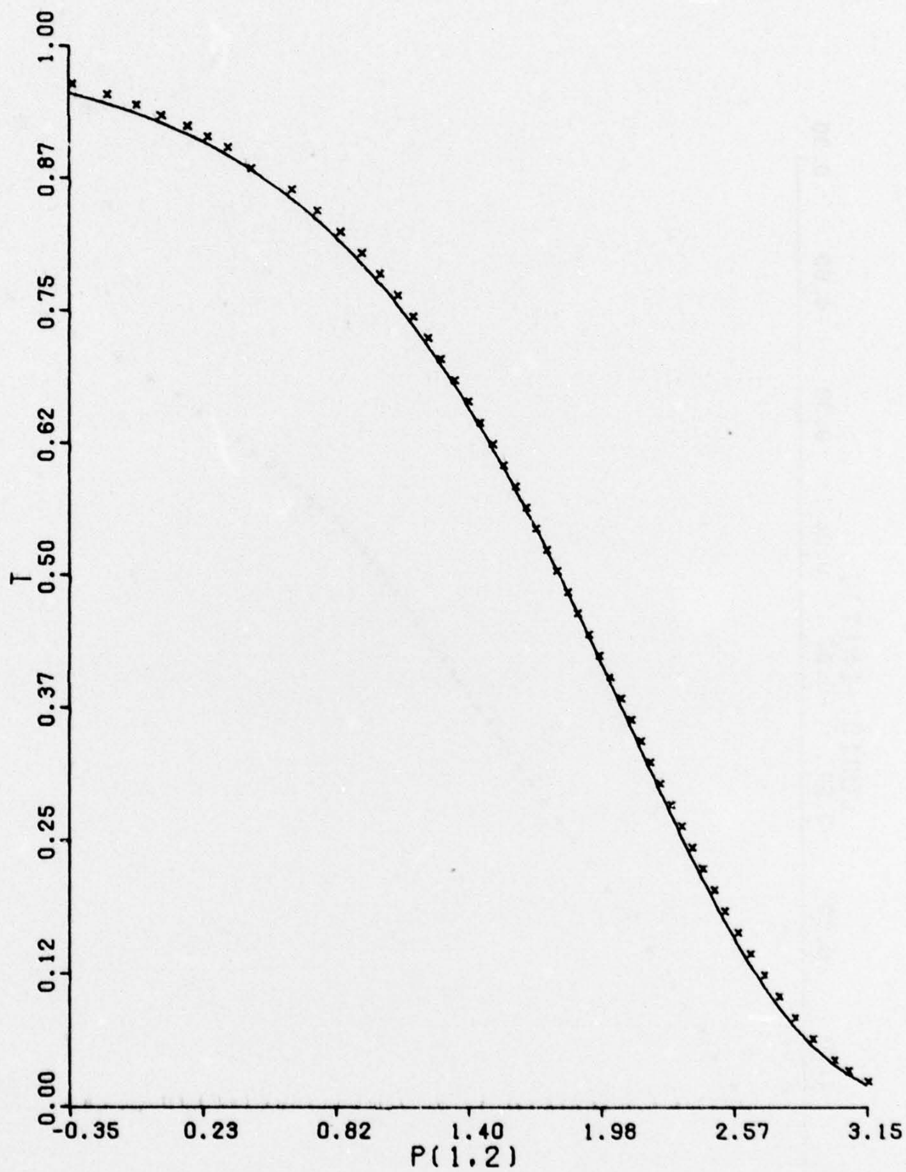

Figure 2. Comparison of $(p_{1,2}(\nu), T_{1,2}(\nu))$ Computer Listed Data (X) and First Order Least Squares Fit Values (-) for Water Vapor Line Structure and Uniformly Mixed Gases

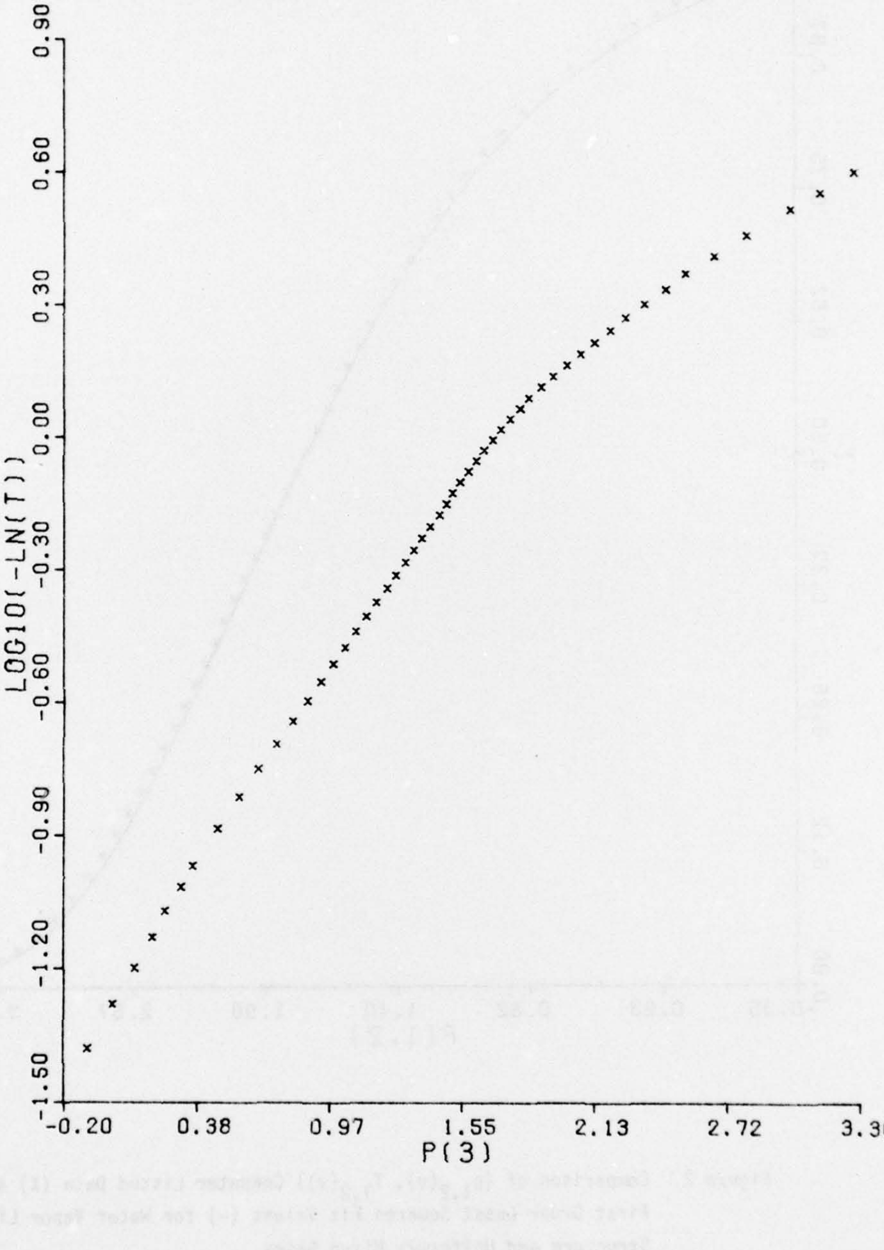

Figure 3. The $(p_3(\nu), \log_{10}(-\ln T_3(\nu)))$ Computer Listed Data (X) for Ozone

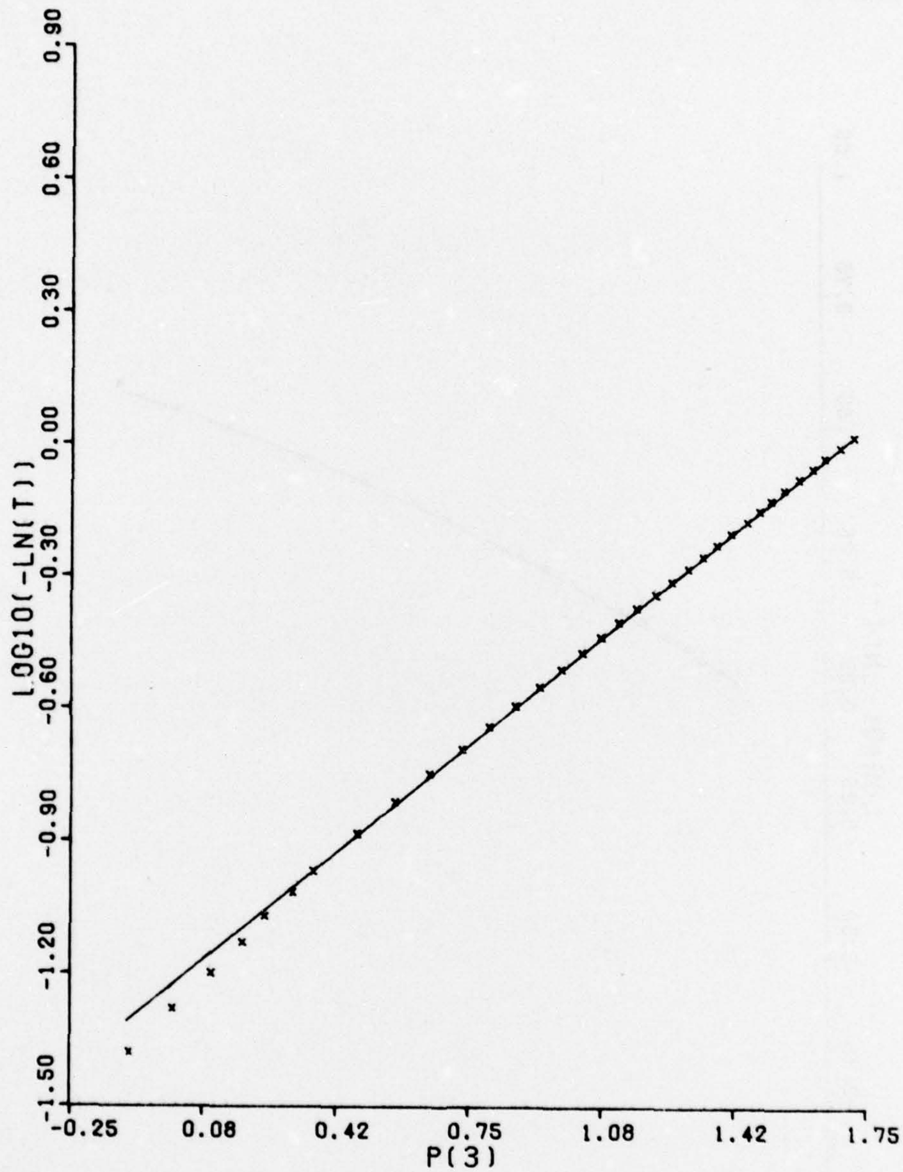

Figure 4. Comparison of $(p_3(\nu), \log_{10}(-\ln T_3(\nu)))$ Computer Listed Data (X) and First Order Least Squares Fit Values (-) for Ozone When $T_3(\nu) \geq 0.36$

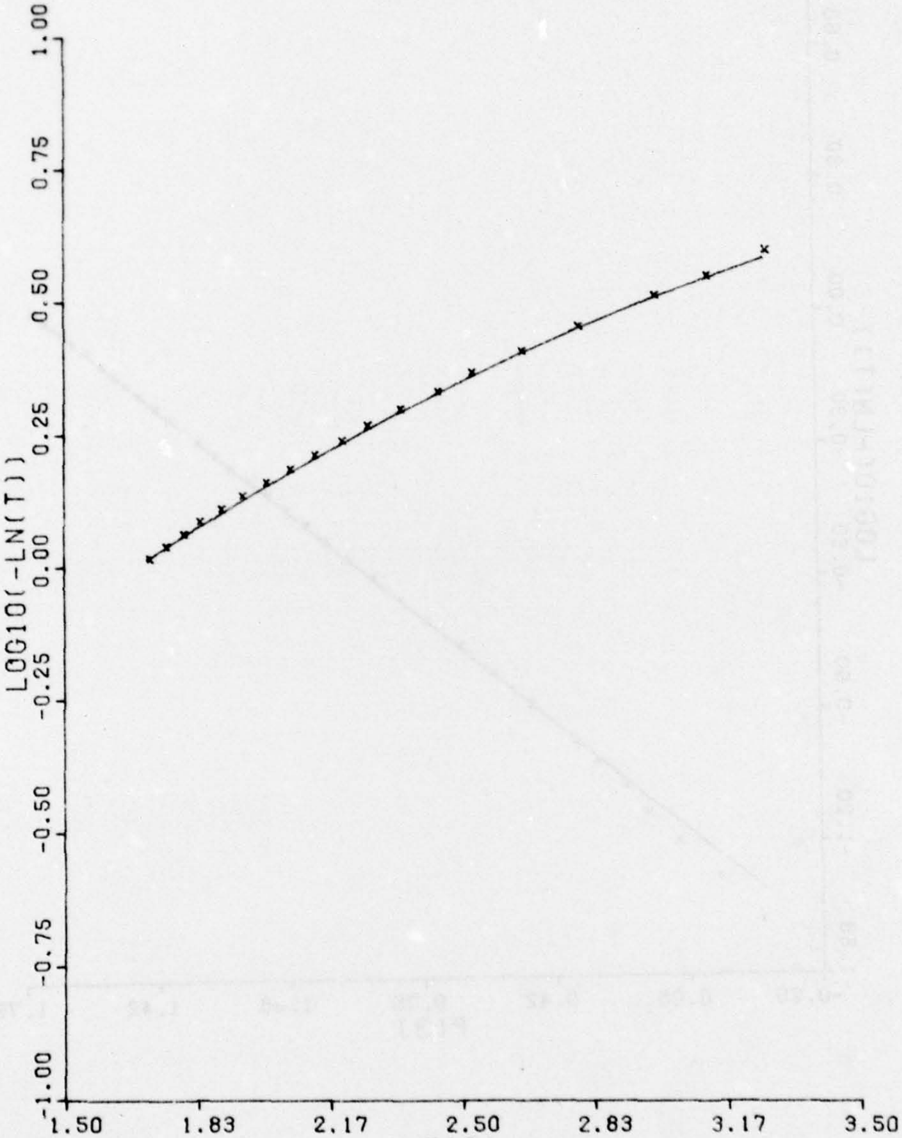

Figure 5. Comparison of $(p_3(\nu), \log_{10}(-\ln T_3(\nu)))$ Computer Listed Data (X) and Second Order Least Squares Fit Values (-) for Ozone When $T_3(\nu)<0.36$

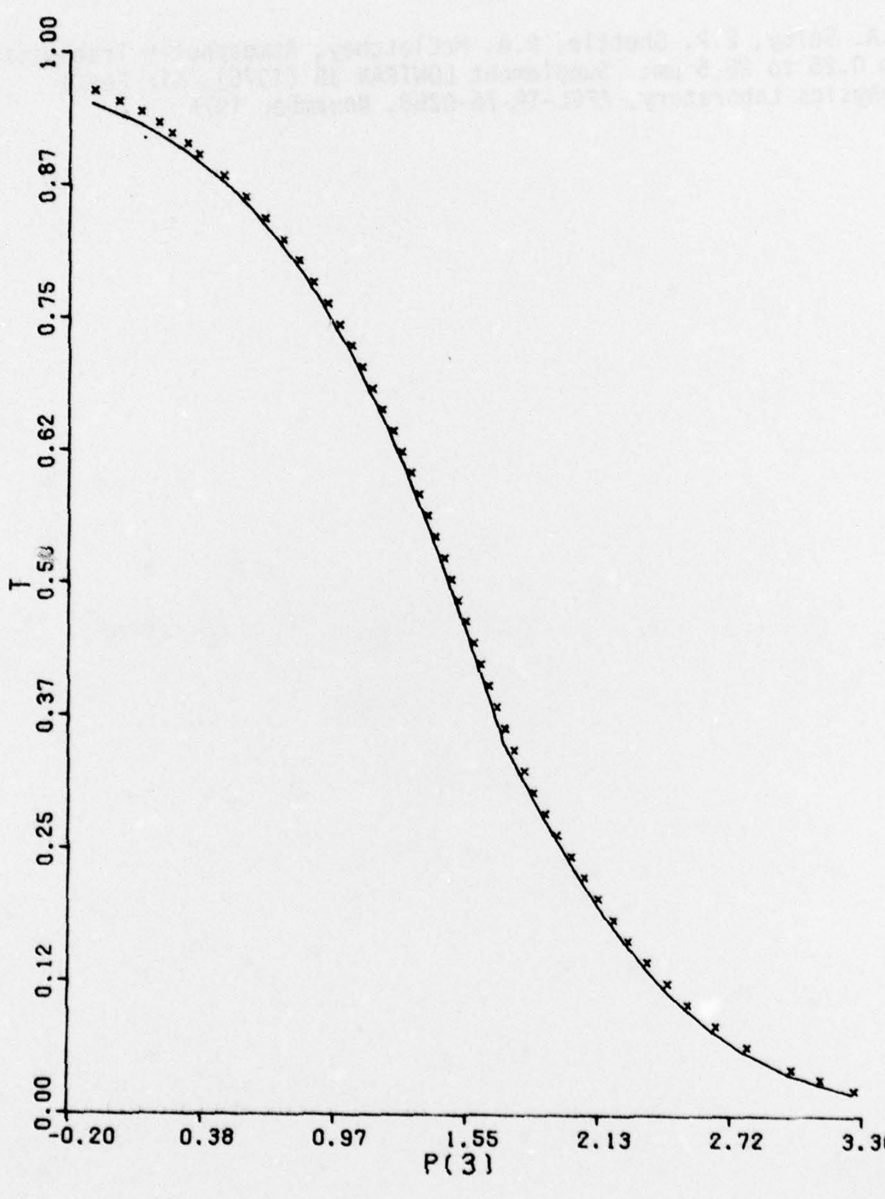

Figure 6. Comparison of ($p_3(\nu)$, $T_3(\nu)$) Computer Listed Data (X) and First and Second Order Least Squares Fit Values (-) for Ozone

REFERENCES

1. J.E.A. Selby, E.P. Shettle, R.A. McClatchey, Atmospheric Transmittance from 0.25 to 28.5 μm: Supplement LOWTRAN 3B (1976), Air Force Geophysics Laboratory, AFGL-TR-76-0258, November 1976.